A White Paper for a US Fusion Nuclear Engineering Program

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Executive Summary

The aim of this white paper is to outline a strategy to develop a US national effort in fusion nuclear engineering to support the accelerated design and construction of a fusion pilot plant. Fusion nuclear engineering incorporates neutronics for fusion devices, including development of methodologies, radiation transport simulations, nuclear integration, and definition of requirements specific to fusion device design for power production. This paper describes needs for: (i) nuclear analysis of a conceptual plant design and assessment, (ii) workforce development, (iii) code development with verification and validation activities, (iv) coordination of national efforts and international collaboration, and (v) identification of requirements for experimental data, including a prototypical fusion neutron source, benchmarks, and nuclear data.

Five specific areas require consistent and sustained activity to contribute to fusion energy development:

1. Blanket and other fusion core and near-core component design
2. Materials damage, transmutation, and subsequent behaviors
3. Accident scenarios, decay heat, activation, and waste
4. Computational and workflow development
5. Verification and validation

The need for work force development is discussed. Although a complete set of relevant data is not available, and various assumptions are made, it is concluded that 10 to 15 new, suitably trained post-graduates are needed each year to support a national program of fusion pilot plant developments. Although the overall number of postgraduates available is likely adequate , training focused only in the main areas of expertise for the fission industry or weapons research (criticality, reactor physics etc.) is not sufficient for fusion nuclear engineering. Additional courses specific to fusion are required for these students to both engage their interest and provide relevant training.

A coordinator of fusion neutronics is proposed to oversee the educational program, to support research, and to ensure the completeness and quality of nuclear analyses for fusion power plant design. The coordinator will guide development and validation of radiation transport codes and will advise experimental research programs to improve the quality of fusion-relevant nuclear data and benchmarks.

Contents

1. Introduction

The aim of this white paper is to outline a strategy to develop a US national effort in fusion nuclear engineering to support the accelerated design and construction of a fusion pilot plant. Fusion nuclear engineering incorporates neutronics for fusion devices, including development of methodologies, radiation transport simulations, nuclear integration, and definition of requirements specific to fusion devices designed for power production. This paper describes needs for: (i) the nuclear analysis of a conceptual plant design and assessment, (ii) workforce development, (iii) code development with verification and validation activities, (iv) coordination of national efforts and international collaboration, and (iv) identification of requirements for experimental data, including a prototypical fusion neutron source, benchmarks, and nuclear data.

The 2021 report from the National Academy of Science, "Bringing Fusion to the US Grid" [1] includes two recommendations:

1. The US should "produce net electricity in a fusion pilot plant in the United States in the 2035–2040 timeframe," and
2. "The Department of Energy should move forward now to foster the creation of national teams […] that will develop conceptual pilot plant designs…"

In December 2020, the Fusion Energy Sciences Advisory Committee (FESAC) made a recommendation to "Initiate a design effort that engages all stakeholders to establish the technical basis for closing critical gaps in a fusion power plant…," and a White House Summit was held in April 2022 at which the US Department of Energy (DOE) launched an initiative to accelerate the viability of commercial fusion. All of these developments point toward the urgent need for qualified science and engineering personnel with specific skillsets that support fusion, and neutronics is one of the most critical of these skillsets.

In simple terms, a fusion power plant must have a set of blanket modules with a cooling system surrounding the burning fuel in a plasma (or a compressed form as in an inertial confinement device). The blanket serves multiple purposes, including tritium breeding, energy capture, and shielding. Openings in the blanket allow access for heating and diagnostic systems. A power plant requires a vacuum vessel, and magnetic confinement devices also require a cryogenic system. The plasma-facing components must be exchanged periodically for economic reasons or in the event of an accident. This indicates the need for remote handling systems, as well as hot cells and decontamination processes. Ensuring that these systems' designs meet all applicable requirements will require extensive neutronics analysis.

Nuclear engineering is a crucial component of the fusion engineering enterprise. It provides nuclear information to other disciplines and directly contributes to critical areas of fusion plant design. Such nuclear information includes nuclear heating to components, activation of in-vessel components, radiation damage to materials, tritium breeding, as well as neutron and γ-ray fluxes and biological dose rates throughout the facility. Neutrons and γ-rays will impact many systems beyond the high intensity fusion core and will have significant impacts and safety implications. Because no existing fusion facilities have neutron production approaching that of a fusion power plant, fusion neutronics requires extrapolation to a regime for which little engineering experience exists. This in itself makes for a unique challenge that must be specifically addressed. Many novel challenges are presented by a fusion power plant that are not faced by conventional fission plants, so it is important that the necessary skills be developed to provide neutronics analyses in a timely manner: that is, as soon as possible. Efforts to introduce students to the specificity of fusion technology will further the initiative to accelerate the viability of commercial fusion power.

2. Neutronics for Fusion

The nuclear analysis portion of the fusion engineering enterprise in fusion energy development is a very important component that provides nuclear information to other disciplines (e.g., thermo-mechanics, computational fluid dynamics, accident/shutdown scenarios, facility systems integration and build, and material specifications), and it contributes directly to critical areas of fusion plant design, such as tritium breeding, material damage/lifetime, shielding, activation/dose, equipment qualification, maintenance, and waste assessment. Nuclear analysis plays such an important role in the design of a fusion plant that **iteration between design and nuclear analysis is needed throughout a project lifetime** for all systems.

A list of nuclear analysis output is provided below, along with some specialized considerations. These factors are largely focused on magnetic fusion energy (MFE), but similar issues arise in inertial fusion energy (IFE):

Heating throughout fusion core components (neutrons and photons), including first wall components, blankets, divertor, in-vessel coils, vacuum vessel, extending all the way out to the toroidal field (TF) and poloidal field (PF) magnets. The integral of the heating provides the dose needed for qualification of insulating components, including some on the tokamak periphery (e.g., insulating pads under gravity supports).

Tritium production in all fusion core components, particularly in breeding materials. This is required to ensure the tritium self-sufficiency of the pilot plant and to support the ultimate assessment of radioactive waste. As part of this, the efficacy of neutron multipliers must also be evaluated.

Material damage, transmutation, and gas production to fusion core components requiring their periodic replacement. These effects extend outward from the neutron source, decreasing in their intensity but still causing critical constraints in material selection and shielding (e.g., vacuum vessel, welds, bolted attachments). The sensitive superconducting magnets are a specific example of near-core impact.

Shielding and activation are a central factor in material selection (structure, coolants, breeder, other functional materials, shields, magnet materials, vacuum vessel, etc.), radial build, and impurity specifications in materials.

Radiation maps during all phases of plant operation and across the entire facility. Production of radiation maps requires modeling of all sources, including plasma, activated coolants, activated machine components, activated building structure, activated air, dust, and corrosion products. Radiation maps must be produced to describe neutron and gamma flux and spectra, biological dose, dose to materials, and 1 MeV equivalent neutron flux throughout the facility.

Shutdown dose rates at fusion core components for inspection, remote maintenance, efforts to maintain radiation exposure to workers, the public, and the environment at levels that are as low as reasonably achievable (ALARA), transport of components, and hot cell impacts.

Afterheat for remote maintenance, safety assessments (e.g., loss-of-coolant accident [LOCA] and loss-of-flow accident [LOFA]) in accident scenarios and normal shutdown and startup.

Quantitative waste generation and classification determines the requirements for storage and ultimate disposal: the fusion energy target is to require only shallow land burial.

Other topics can include neutron streaming, breeding enhancements, validation against experiments, nuclear data, safety factors, Li burnup in solid breeders, multiple breeding blanket comparisons, and so on.

In an IFE plant, high-Z materials such as Pb hohlraums, Au cones for fast ignition, or dopants for indirect-drive capsules (e.g., tungsten) could be present in the target. If these materials are close to the fuel capsule, then they will be exposed to very high neutron fluxes, leading to more exotic reactions not typically seen with the lower fluxes in magnetic confinement devices, such as (n, xn).

Personnel must possess significant experience in radiation transport simulations to conduct these analyses. Currently, this is typically accomplished using sophisticated simulation software. The most commonly used software was developed for fission systems, so experience with such codes provides a work force with skills applicable across the nuclear industry. The specific skills needed to determine neutronics for fusion are related to *nuclear integration*, which is the design and development of systems that account for the impact radiation has on the systems and how the nuclear response of other systems is affected. This area of expertise is closely coupled to nuclear engineering but performing this work for fusion plants requires significant specific training to provide engineering solutions that address simultaneous and often conflicting requirements related to nuclear shielding, activation, plasma-wall interactions, magnetism, plasma stability, and so on. Clearly, neutronics for fusion demands specific training and expertise.

Five specific areas in nuclear analysis require consistent, sustained activity to advance fusion energy development:

1. Blanket and other fusion core and near-core component design
2. Materials damage, transmutation, and subsequent behaviors
3. Accident scenarios, decay heat, activation, and waste generation
4. Computational and workflow development
5. Verification and validation

Nuclear issues requiring research and development (R&D) beyond the more common focus on fusion reactor design and assessment include the following:

1. Nuclear data for fusion applications
2. Development of experimental fusion neutron sources
3. Activated corrosion products
4. Shielding materials
5. Remote handling
6. Radiation-hard electronics

Organizations that have supported computational development of nuclear analysis tools include University of Wisconsin – Madison, Oak Ridge National Laboratory (ORNL), and Argonne National Laboratory. As the largest materials laboratory in the US program, ORNL is now also the location for the Blanket and Fuel Cycle program's simulation and design (and previously FESS design activities), the High Flux Isotope Reactor (HFIR), the Material Plasma Exposure Experiment (MPEX), and US-ITER. Therefore, ORNL is the ideal location for fusion core design and materials development for the program. These programs should be coordinated to support ITER, fusion pilot plant (FPP) design, and public and private fusion research in general.

Current licensing regulations for fission power plants and accelerators are not well suited to the licensing of fusion plants. However, issues related to nuclear safety and radiation protection will still be a significant part of fusion plant licensing issues. Neutronics will be a significant factor when determining the parameters to ensure plant safety, to determine the radiation environment, to establish qualification requirements for equipment, to estimate damage to materials, and to estimate waste generation. Neutronics will also be a key factor when defining shielding requirements and health physics monitoring. Impartial advice to the US Nuclear Regulatory Commission (NRC) and private industry will be essential to development of a fusion pilot plant, and there are precedents for national laboratories to contribute to this area.

3. Workforce Development

The report from the 2022 US ITER Research Program Needs Workshop [2] recommended "support [for] education and preparation of the workforce needed to deploy fusion energy… An inclusive, equitable fusion workforce, prepared by education and experience gained in our schools, universities, labs, and private companies, is needed to contribute to and benefit from ITER."

This white paper is presented in the light of these recommendations. The need to expand the nuclear workforce in the areas of technology and engineering is widely recognized. It is appropriate to ask if particular attention is needed for fusion nuclear engineering and/or neutronics expertise. Training in neutronics generally focused on reactor physics and weapons applications provides some relevant skills suitable for the fusion reactor design, but knowledge gaps would remain in specific fusion engineering training. The differences arise because of the complexity of fusion reactor geometry. Although expertise in criticality and reactor physics is not needed, the requirement to analyze very large, detailed geometries, to compute and simulate many different sources of radiation, and to calculate tritium breeding and damage are all unique to fusion. As mentioned above, there are no existing fusion facilities whose neutron production approaches that of a fusion power plant. The entire neutron budget of Joint European Torus (JET), the world's largest and longest running deuterium–tritium (DT) tokamak, will be exceeded after ten seconds of operation in a machine such as ITER operating at 500 MW. Therefore, fusion neutronics requires extrapolation to a regime for which there is no current engineering experience.

It is proposed to leverage the extensive fusion (and fission) neutronics experience at ORNL and other national laboratories to help develop collaborative programs with universities to build up the required work force and to support a fusion pilot plant development program and ITER. Development of neutronics expertise in fusion is complementary to and synergistic with the nuclear fission industry, particularly in the coordinated efforts to move to a low- (and non-) carbon emission energy production.

The American Nuclear Society (ANS) approached the Nuclear Engineering Department Heads Organization (NEDHO), for "updates on their programs and to detail their areas of special interest." Twenty universities responded [3] , 8 of which explicitly mentioned interests in fusion or radiation transport:

Georgia Institute of Technology

Massachusetts Institute of Technology

Oregon State University

Pennsylvania State University

Rensselaer Polytechnic University

University of Wisconsin-Madison

Virginia Commonwealth University

Virginia Polytechnic Institute and State University

Although the University of Tennessee – Knoxville (UTK) did not mention fusion or radiation transport in their description of the department, they have performed significant work in the fusion neutronics area. Therefore, this review is not completely reliable, and further investigation is warranted.

Wisconsin-Madison and Massachusetts Institute of Technology (MIT) are two established universities in this technical area, but at this early stage, it is appropriate to cast a net widely and determine whether other universities are interested in increasing their fusion neutronics programs. Some examples include the following:

North Carolina State University

University of Michigan – Ann Arbor

Texas A&M University

University of Illinois, Urbana-Champaign

South Carolina State University (the only four-year historically black college or university (HBCU) offering a four-year nuclear engineering degree)

A white paper was presented on advancing the fusion technology workforce by the University of Wisconsin-Madison Fusion Technology Institute (UW-FTI) at the APS-DPP Community planning workshop [4] . The UW-FTI was established in 1971 and is the largest program in the United States for advanced degrees in fusion energy. The UW-FTI graduates occupy key management positions in US industry and at national laboratories and universities. The white paper highlighted the 10 key focus areas listed below for continued fusion workforce development based on the perspective of the well-established program at UW-FTI. More details for each of these items are available in their white paper [4] .

1. Continue teaching broad-base fusion technology courses
2. Continue offering fusion technology options for senior undergraduate design class
3. Continue offering fusion technology options for semester projects in other classes
4. Develop and offer a "Fusion Technology" master's of science degree
5. Increase the number of funded graduate students in the fusion technology degree program
6. Develop new undergraduate internships with local private fusion start-up companies
7. Develop advanced fusion technology courses in areas such as fusion neutronics
8. Develop online versions of currently offered fusion technology courses to facilitate remote participation by other university students
9. Increase training of professionals interested in fusion technology (mini-courses ranging from 1–4 days depending on topic and depth of coverage)
10. Assure the knowledge transfer of soon-to-retire or recently retired fusion technology experts

Expanding fusion technology to other universities may require that new faculty be hired at those universities, or add-on training may be required for existing faculty in fusion-specific areas. For example, fission neutronics experts have good baseline knowledge of neutron and gamma physics, but there are some key differences in neutronics and reactor design issues between fission and fusion. These aspiring mentors could be efficiently brought into fusion by having a fusion-specific mentor from an established fusion neutronics program.

The following steps are recommended:

1. In the short term, ORNL will canvas US universities and discuss the development of courses within existing nuclear engineering programs to increase training in neutronics for fusion reactors.
2. Adapt the US Particle Accelerator School model to train a new workforce in fusion neutronics [5] . The extensive experience within ORNL will be exploited to design the course content and to ensure its relevance to the development of fusion pilot plants.
3. The majority of students have generally already committed to a particular subject or have one in mind by the time they are in graduate school. However, students at this level can still be engaged while they are still in generic nuclear engineering classes. The fusion community must take advantage of existing internship programs to encourage interest in fusion nuclear engineering research. Such programs include Science Undergraduate Laboratory Internships (SULI) [6] , Community College Internships (CCI) [7] , Reaching a New Energy Sciences Workforce (RENEW) [8] , and Funding for Accelerated Inclusive Research (FAIR) [9] mentoring and internships. These can be implemented by national labs and private industry. The Fusion Energy Sciences (FES)-RENEW and Office of Science (OS)-FAIR funding opportunity announcements to develop an equitable, inclusive workforce in the fusion neutronics community should also be utilized.
4. Adapt a nuclear engineering course to include fusion nuclear engineering minors. National labs should work to define these courses.
5. Make regular presentations at seminars, colloquia, and student conferences.

Sustainable jobs must be available for when this workforce graduates. Therefore, industry, labs, and universities must work together and make a concentrated effort to predict the needs and to provide funding for the new positions to be filled and sustained.

Other technical disciplines upon which fusion relies must also be explored at these universities, including thermomechanics, fluids including liquid metals, materials science, and hydrogen science. Development of these disciplines will ensure an even more comprehensive fusion workforce.

The remainder of this paper presents the areas where additional R&D effort is needed, proposes a nuclear analysis program, and discusses the resource requirements.

4. Code and Workflow Development

Neutronics simulations are complex calculations that solve the radiation transport equations in general geometry, and the resulting radiation fields are combined with additional analyses to generate the quantities of interest (tritium breeding ratio, damage, transmutations, decay heat and activation, and waste). Computational techniques are critical to accuracy and efficiency in fusion energy. These techniques must be continually developed to enable flexibility, to expedite enhancements, and to **take advantage of improved computing platforms**. These **nuclear calculations produce critical information upon which designs are based**. The calculations are deemed successful or unsuccessful, and they are validated against experiments to advance development of fusion energy.

In order for nuclear analysis to provide timely results that allow iteration on a design, workflow improvements are required. This could be achieved in part by developing rapid scoping calculational techniques, which will require validation. Further R&D is needed in the areas of conversion of CAD models to radiation transport models and to perform data visualization. These objectives and the areas mentioned above are also common to fission, but the complexity of fusion systems significantly extends the requirements.

The simulation tools developed for nuclear analysis must handle the complexity of the geometry of fusion systems, the complexity of progressively more detailed designs, and the expansion of modeling to buildings and other more distant locations. It is not clear that one approach to generate models for nuclear analysis is superior to the others. There are often trade-offs in which individual approaches excel in one or more areas at the expense of others.

Coupling neutronics codes that calculate quantities more common in IFE solutions, such as electromagnetic pulse (EMP) or debris generation, should also be investigated.

There is now a wider choice of codes, and several of them are undergoing aggressive development. It is not possible currently to determine which if any of the areas of development is especially promising. Centralized coordination of these efforts is required, along with validation, maintenance, and distribution. Central coordination was successfully implemented at ITER, and that experience can be extrapolated for this effort. The ITER coordination led to developments in modeling [10] , data visualization, variance reduction [11] , the use of CAD [12] [13] tool sharing [14] improved algorithms for the Monte Carlo N-Particle (MCNP) code for large-scale models [15] , standardized seismic design (SDD) tools [16] , advanced variance reduction [17] , and more. This was achieved by several institutions who worked under their own initiatives with direction from ITER. It was important to consider current developments in nuclear analysis technology and detailed knowledge of machine design as it evolved. **A similar central coordination should be implemented for this effort.**

5. Verification and Validation

Sophisticated nuclear analysis tools are often tested against one another via code-to-code benchmarks using established tools. This approach is the primary method used to ensure accuracy and technical fidelity, and it is the most accessible, practical approach for verification. Benchmark experimental data (reference cases) are sometimes used, but these are often highly simplified and do not represent the complexity of a fusion facility. Although only limited validations have been performed (Frascati Neutron Generator - Energia Nucleare ed Energie Alternative [FNG-ENEA], Fusion Neutronics Source - Japan [FNS-JA]), they are critical for identifying the total computational–experimental error and for launching explorations into the error contributions (e.g., nuclear data, model, experimental data, computational fidelity). Other forms of validation address complexity, such as the JET nuclear comparisons being performed on a tokamak experiment with many hardware components and materials that influence the neutron source measurement at a detector. In addition, plasma can provide an atypical neutron source in various operating regimes. ORNL has had a long-standing collaboration with EUROfusion on the JET shutdown dose rate (SDDR) and neutron streaming benchmark series [18] but this area must improve significantly for fusion energy development to progress. The critical nature of improving nuclear data, libraries, nuclear models, and experimental testing is recognized outside the United States, but domestic efforts are limited [19] .

Validation (comparison of simulation to experiment) must occur in virtually all areas, including tritium breeding, heating, transmutation, and gas production—especially in integrated systems with multiple materials. Some challenging issues in this area include the activation of dust in the plasma chamber and corrosion products in the fusion core. A wide range of materials are anticipated in the fusion reactor, including metals, insulators, ceramics, coatings, magnets, shields, and fluids, and these must be tested in the appropriate environments. For example, for magnets, a mixed spectrum fission reactor like HFIR may be sufficient. Several experiments at the FNG-ENEA DT source on integrated assemblies have shown computation/experiment errors ranging from 5–25%, most of which worsen with distance from the source. Areas in which testing is significantly lacking include Monte Carlo methods for large facilities, sky shine, fluid activation, and moving sources.

Nuclear data evaluations relevant to the various fusion applications (e.g., ITER, Fusion Prototypic Neutron Source, Fusion Pilot Plant) are necessary to guarantee the high accuracy of nuclear analysis and to provide confidence to project to new operating regimes. This includes nuclear data for neutron-, proton- and deuteron-induced reactions; generation of associated covariance data for uncertainty analysis; development of advanced nuclear models; processing and benchmarking of the evaluated data against integral experiments; and development of software tools for sensitivity and uncertainty analysis of fusion systems. ORNL has had a leadership position in the Organisation for Economic Cooperation and Development - Nuclear Energy Agency (OECD-NEA) efforts under the Working Party on Scientific Issues and Uncertainty Analysis of Reactor Systems / Expert Group on Radiation Transport and Shielding (WPRS/EGRTS) (previously) and the Expert Group of Physics Reactor Systems (EGPRS) (currently) responsible for updating the Shielding Integral Benchmark Archive and Database (SINBAD). International efforts are ongoing for fusion-specific nuclear data, and the United States should develop domestic capability and also collaborate on the existing international activities.

Improved nuclear data are required, but its development must be carefully planned by first assessing the sensitivity of various nuclear parameters to the nuclear cross-section libraries. This shall be accomplished by creating a library of 1D to 2D builds representing fusion device concepts. This library should include various structural materials, breeder materials, functional materials, and coolants typically used in fusion designs. 1D and 2D analysis can very rapidly indicate which cross section and/or reactions are important in pilot plant design. In conjunction with existing and current nuclear library and nuclear model assessments, an experimental program to improve the data should then be instigated.

Suitable neutron sources that represent the associated in-service environment in a fusion reactor, including accelerators, fission reactors, and DT fusion (14 MeV neutrons and neutron emission >10^{10}n/s are preferred for the fusion core) must be available for these experiments. A much more intense neutron source, such as a fusion prototypic neutron source, is required for materials degradation studies [20] .

The objective of the Fusion Evaluated Nuclear Data Library (FENDL) project [21] is to assess and recommend existing nuclear data for fusion applications, but the project is currently limited in scope and would greatly benefit from this proposed systematic study. Furthermore, FENDL data libraries must be expanded to cover energies up to 30 MeV. In the National Ignition Facility (NIF), the reaction in flight (RIF) neutron spectrum expands to that energy range, and something similar may be possible with IFE.

6. National Coordination

Coordination of neutronics should be well integrated with the coordination of other aspects of the fusion engineering enterprise. As designs for a fusion pilot plant progress, a range of engineering disciplines is required, in addition to neutronics, including thermomechanics, materials, coolant fluid CFD, liquid metal CFD, tritium migration and process behavior, electromagnetics, thermal hydraulics, and plasma behaviors. The materials used and the geometry and strategies for fusion differ from any other engineering endeavor, including fission, and they require training and exposure to develop the required skillsets. Collaborating with universities in terms of neutronics and the other required engineering and plasma disciplines is the most efficient and practical.

In addition to the university connection for training and development of nuclear analysts and other engineering disciplines for fusion, overall coordination is needed across the national program to create and sustain the efficient development of tools, testing and validation, connection to nuclear data improvement, and documentation. This white paper primarily addresses the need to coordinate neutronics within the fusion program. Other transverse disciplines (e.g., electromagnetic analysis) also require coordination, and neutronics coordination must also be coupled to them.

A coordinator role for fusion neutronics for U.S. domestic programs is proposed. This should be more than an advisory role; it should also ensure implementation of nuclear integration within the fusion program in line with the directives of the Office of Fusion Energy Science. This role requires in-depth technical knowledge of fusion neutronics, as well as broad expertise in fusion power plant design sufficient to interact with other specialists in the field. Furthermore, the position requires a coordinator of international standing to support the work on ITER and to engender collaboration on an international level given the many national fusion research programs currently underway.

7. Resources for Nuclear Analysis of Fusion Pilot Plant Design

To estimate the resources required to support the design of a fusion pilot plant, one can look at the experience of ITER. During the conceptual design phase, the nuclear analysis group of ITER and the home team members who contributed to the nuclear analysis report (which formed the cornerstone of the ITER design) consisted of 33 people.

The overall neutronics resources employed by ITER cannot be easily quantified. There were five ITER staff members, but a substantial amount of work was carried out by staff at the domestic agencies and by staff contracted by the domestic agencies or ITER. Attendance at the annual ITER neutronics meetings can serve as an indicator of the number of staff members supporting the project. The figure below shows the number of attendees at each meeting for cases in which data were available. The average number of attendees was 35. Not all attendees were directly involved in neutronics: some were code developers, and some filled other roles. However, each attendee usually represented several other analysts from their home institutions. Based on experience with ITER, an estimate of 15 nuclear analysts for one device is not overly conservative.

The table below lists the number of nuclear engineering degrees obtained in the US from 2010 to 2019. 60% of graduates reported employment with nuclear utilities, nuclear related organizations, or DOE. Assuming that the numbers stay the same as in 2019, 116 graduates will go to work in the nuclear industry. In the absence of data regarding the fraction of attendees who work in fusion and non-fusion areas, the assumption is made that 20% pursue careers into fusion, for a total of 23 staff members per year. A fusion pilot plant's design period can be expected to last ten years. If the average career length is assumed to be five years, then the probability of losing one staff member is 11% per year. In a team of 15, that is 2 or 3 per year. Universities must train post-graduates at sufficient rates to replace these personnel. If four or five FPPs are being designed in the United States, then 10 to 15 staff members must be trained annually. If the fraction of post-graduates who continue to go into industry is 10%, then 100 to 150 graduate training courses must be completed each year. Therefore, the number of postgraduates projected is likely adequate. However, it should be noted that training in the main areas of expertise for the fission industry or weapons research (criticality, reactor physics, etc.) is not sufficient for fusion nuclear engineering. Courses specific to fusion are required to excite the students' interest and to provide relevant training.

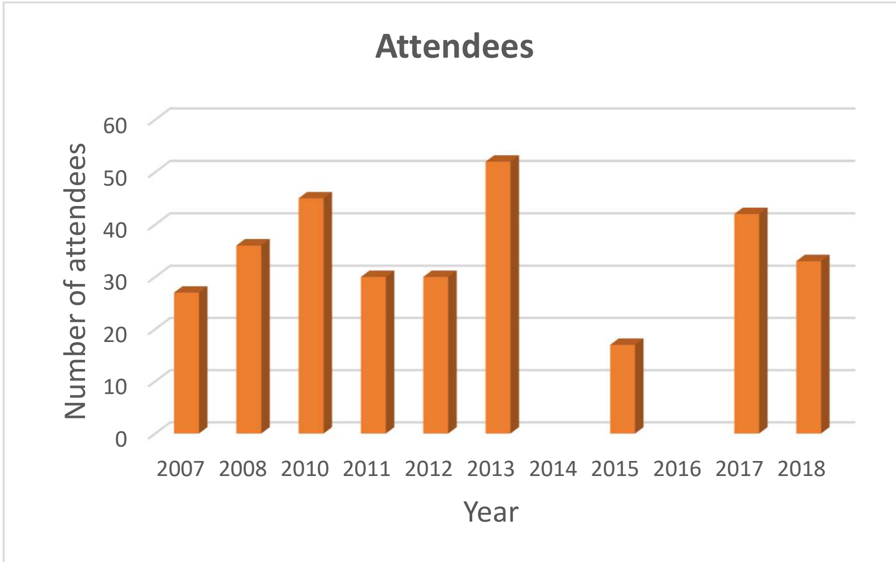

Figure 1: Number of attendees at the ITER neutronics meeting during ITER's construction phase.

Table 1: Number of nuclear engineering degrees in the US, 2010–2019

Year	B.S.	M.S.	Ph.D.
2019	622	316	194
2018	623	260	195
2017	619	282	170
2016	621	355	161
2015	652	363	147
2014	627	322	169
2013	655	362	147
2012	610	333	119
2011	524	277	113
2010	443	303	113

Source: Oak Ridge Institute for Science and Education

Additional resources will be needed to support the program for nuclear data, materials modeling, and development of a fusion neutron source, including interpretation of results. This amounts to about 5 people but overlap with the fission industry could be used.

8. Conclusion

To engender a base of expertise for the design and development of a fusion pilot plant, it is necessary to encourage, mentor, and coordinate universities and national laboratories in nuclear analysis for fusion reactors. ORNL proposes to help define the educational and research programs directly relevant to the accelerated deployment of fusion reactors to the US grid and to assist in the execution of these research programs. Contributions from other national laboratories are desired. This program would also help rekindle the expertise in the US nuclear industry as a whole and would provide a comprehensive capability that includes computational development, detailed applications, and verification and validation activities.

Creation of a coordinator of fusion neutronics to oversee the educational program, to support research, and to ensure completeness and quality nuclear analyses for the design of fusion power plants is also proposed. The coordinator would also have the responsibility to guide the development of radiation transport codes, to ensure their validation, and to advise on the experimental research programs to improve the quality of fusion-relevant nuclear data and benchmarks.

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10. References

[1] National Academies of Sciences, Engineering, and Medicine 2021. "Bringing Fusion to the US Grid." Washington, DC: The National Academies Press. https://doi.org/10.17226/25991.

[2] C. Greenfield and C. Collins, "Report of the US ITER Research Program Research Needs Workshop" https://www.iterresearch.us/.

[3] https://www.ans.org/news/tag-university%20programs/

[4] T.D. Bohm, "Advancing Fusion Technology Workforce Development at the University of Wisconsin-Madison Fusion Technology Institute," APS-DPP Community Planning Workshop, July 22–26, 2019, Madison, WI, https://www.google.com/url?q=https://drive.google.com/open?id%3D16VeW3KBvEY-zQGk8SEJTLYykm9V1xOUe&sa=D&source=editors&ust=1675721743846791&usg=AOvVaw3ziEATj0xB-iokpn3ER0Ef

[5] "US Particle Accelerator School: Education in Beam Physics and Accelerator Technology," https://uspas.fnal.gov

[6] DOE, "Science Undergraduate Laboratory Internships (SULI),"

[7] US Department of State, "Community College Initiative Program," https://exchanges.state.gov/non-us/program/community-college-initiative-program#:~:text=The%20Community%20College%20Initiative%20Program,in%20their%20fields%20of%20study.

[8] DOE, "Reaching a New Energy Sciences Workforce (RENEW)," https://science.osti.gov/Initiatives/RENEW

[9] DOE, "Funding for Accelerated, Inclusive Research (FAIR)" https://science.osti.gov/Initiatives/FAIR

[10] R. Juárez, G. Pedroche, et al., "A Full and Heterogeneous Model of the ITER Tokamak for Comprehensive Nuclear Analyses," *Nature Energy* 6 (2021) 150–157. https://doi.org/10.1038/s41560-020-00753-x

[11] A. Davis and A. Turner, "Application of Novel Global Variance Reduction Methods to Fusion Radiation Transport Problems," International Conference on Mathematics and Computational Methods Applied to Nuclear Science and Engineering (M&C 2011) Rio de Janeiro, RJ, Brazil, May 8–12, 2011.

[12] Y. Wu, F.D.S. Team, "CAD-Based Interface Programs for Fusion Neutron Transport Simulation," *Fusion Eng. Des.* 84 (2009) 1987–1992.

[13] E.D. Biondo, A. Davis, P.P.H. Wilson, "Shutdown Dose Rate Analysis with CAD Geometry, Cartesian/Tetrahedral Mesh, and Advanced Variance Reduction," *Fusion Eng. Des.*, 106 (2016), 77–84

[14] GitHub, fusion-energy/magnetic_fusion_openmc_dagmc_paramak_example

[15] S. W. Mosher and S. C. Wilson, "Algorithmic Improvements to MCNP5 for High-Resolution Fusion Neutronics Analyses," *Fusion Science and Technology*, 74:4 (2018), 263–276, DOI: 10.1080/15361055.2018.1496691.

[16] S. C. Wilson, S. W. Mosher, K. E. Royston, C. R. Daily, and A. M. Ibrahim, "Validation of the MS-CADIS Method for Full-Scale Shutdown Dose Rate Analysis," *Fusion Science and Technology* 74:4 (2018), 288–302, DOI: 10.1080/15361055.2018.1483687

[17] S.W. Mosher et al., ADVANTG, ORNL/TM-2013/416 (2013).

[18] B. Kos, G. Radulescu, R. Grove, R. Villari, P. Batistoni, and JET Contributors, "Comprehensive Analysis of Streaming and Shutdown Dose Rate Experiments at JET with ORNL Fusion Neutronics Workflows," *Fusion Science and Technology* 79:3, (2023) 284–304, DOI: 10.1080/15361055.2022.2129182

[19] U. Fischer et al, "Nuclear Data for Fusion Technology – the European Approach," EPJ Web of Conferences 146, (2017), 09003: DOI: 10.1051/epjconf/201714609003.

[20] EPRI, "Program on Technology Innovation: 2022 Fusion Prototypic Neutron Source (FPNS) Performance Requirements Workshop Summary," https://www.epri.com/research/products/000000003002023917

[21] U. Fischer et al., *Benchmarking of the FENDL-3 Neutron Cross-Section Data Library for Fusion Applications*, International Atomic Energy Agency Report, INDC(NDS)-631, (2014).